Wave-Current Interaction in Coastal Inlets and River Mouths

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LONG-TERM GOALS

The wave-driven dynamics of coastal areas are important for circulation and mixing, transport processes, and accessibility by vessels. The long-term goal of this study is to improve our understanding, observational capability, and model representation of wave-current interaction in complex coastal inlets, and determine the role of nonlinearity and inhomogeneity on wave statistics in such areas.

OBJECTIVES

The specific objectives of this study are to: 1) develop observational capability using wave- and current-resolving Lagrangian drifters to study wave-current interaction, and contribute to a comprehensive community data set of coastal inlet and river mouth processes, 2) better understand the role of current shear, wave inhomogeneity and nonlinearity in wave-current interaction through analysis of observations and modeling, and 3) develop predictive modeling capability of wave statistics in a complex coastal environment with two-dimensional bathymetry and currents.

APPROACH

To better understand interactions between waves, currents and topography in a coastal inlet, and improve predictive capabilities, we propose an integrated study that combines field observations acquired using newly developed drifter buoys, with advances in theory and numerical modeling of wave-current interaction, random wave focusing and wave dissipation.

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WORK COMPLETED

Instrument development and validation

We continued the development of GPS-tracked Lagrangian drifter buoys that can resolve both surface currents and waves. To augment the GPS measurements, which are very accurate at lower (swell) frequencies and horizontal motions but have limited accuracy for higher frequencies and vertical motions,, the new Wave-Resolving-Drifter (WRD) buoys are equipped with off-the-shelf IMU packages. These sensors are more responsive at higher frequencies that are of interest to characterize the wind-wave spectrum, and provide the resolution of the vertical motions that is lacking in the GPS sensor. The newest (third generation) WRDs (figure 1) have an integrated GPS/IMU sensor platform, controlled by a central micro-controller. These WRD sample faster (5Hz), are more energy efficient, and are equipped with Iridium satellite communication for real-time data collection and position tracking. The new WRDs were successfully deployed in the Mouth of the Columbia River experiment, discussed below.

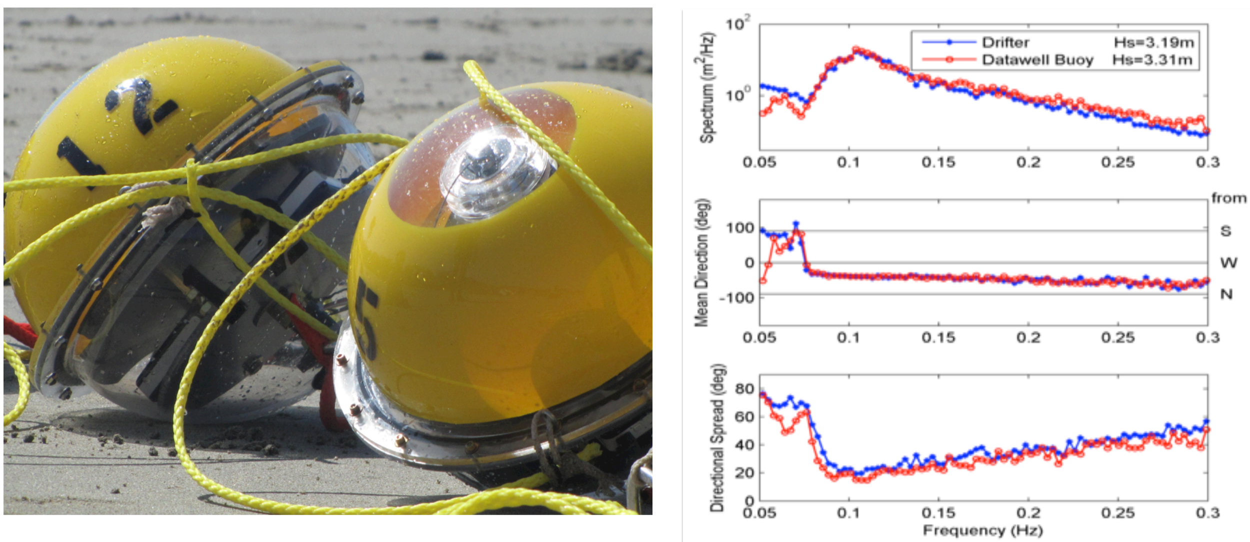

Figure 1 Left panel: The newest (third generation) Wave-Resolving Drifter (WRD). Right panels: Comparison of spectral estimates from the WRD and Datawell Directional Waverider buoy. These observations were obtained in energetic swell (3.3 m significant wave height) in deep water off the coast of Monterey. Spectral estimates are based on a 3 hour-38 minutes-long data record. Drifter-measured surface height spectrum (estimated from the GPS horizontal Doppler velocity data), and directional wave propertiees (based on accelerometer-GPS velocity cross-spectra) are in excellent agreement with Datawell estimates.

Field validation tests of the WRD were conducted on several occasions in deep water off the central California coast by deploying them alongside a Datawell Waverider. An example validation result is shown in figure 1. The drifter-measured surface height spectrum (estimated from the GPS horizontal Doppler velocity data) is in excellent agreement with the Datawell estimate (upper right panel). Directional wave measurements (based on accelerometer-GPS velocity cross-spectra), also agree well with the Datawell estimates (lower two right panels of Figure 1).

Raccoon Strait Experiment

We conducted several experiments in Raccoon Strait located inside San Francisco Bay (Figure 2) to test instruments and collect a comprehensive dataset of wave-current interaction in this area. In addition to free-floating (Lagrangian) WRD drifters, we deployed two bottom-mounted ADCP instruments to

combine Lagrangian and Eulerian observations of the flow and wave dynamics. We also used a ship-board ADCP and a CTD to capture current and stratification characteristics.

ADCP and CTD measurements (not shown) indicate strong internal hydraulics in the lee of the sill that may play an important role in the surface wave dynamics. During the flood tide, surface waves appear to get trapped between the sill (maximum current velocity) and an outcropping front developing between the incoming ocean water and fresher surface waters in the lee of the sill (see Figure 2 for photograph of surface waves). As the flood develops, the denser ocean water plunges underneath the fresher bay water, and the flood current develops what appears an internal lee-wave behind the sill.

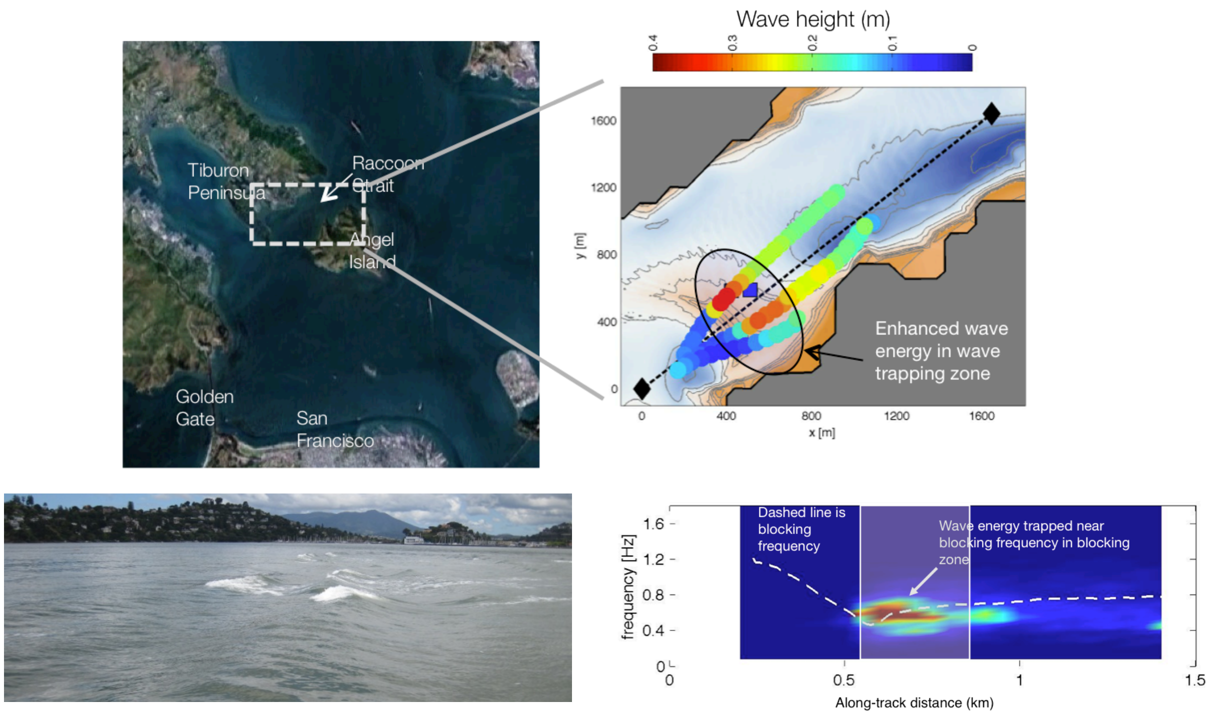

Figure 2 Observations of wave blocking in a tidal flood current. Upper left: Geography of Raccoon Strait inside San Francisco Bay. Lower left: Breaking waves as seen from R/V Questuary over the sill in Raccoon Strait opposing a developing flood tide. Upper right: wave height observations from multiple drifters show strong amplification just east of the sill where the tidal current speed is maximum. Lower right: spectrogram of one of the drifters, plotted versus distance (same scale as the upper right panel) shows the amplified wave energy is concentrated around the blocking frequency where the wave group speed equals the opposing current speed (from Janssen et al., 2013, manuscript in preparation).

Surface wave energy is enhanced in the blocking zone (see Figure 2) where the waves are relatively steep and breaking occurs. From a directional analysis (not shown), based on observations of horizontal and vertical motions, it is seen that the higher-frequency waves (> 0.3 Hz) propagate in opposite direction on either side of the blocking point.

These initial observations reveal a complicated interaction between tidal currents, stratification, topography and surface waves. We focus our study in this area on detecting the origin of the surface wave energy and its directional properties (using the WRD), and identifying the effects of the internal hydraulics on the surface dynamics (using Eulerian instruments). A manuscript summarizing these findings is in preparation.

Golden Gate Experiment

We conducted several large (15-35) drifter deployments in the Golden gate during ebb tides. It was encouraging to see that the WRDs can be used in this challenging environment with heavy ship traffic, strong currents and large waves, to study the ebb current structure, and capture regional variations in the waves (see figures 3 and 4). Observations from February 15, 2012 shown in figure 3 reveal a complicated coastal current structure and large variations in wave conditions along the drifter tracks.

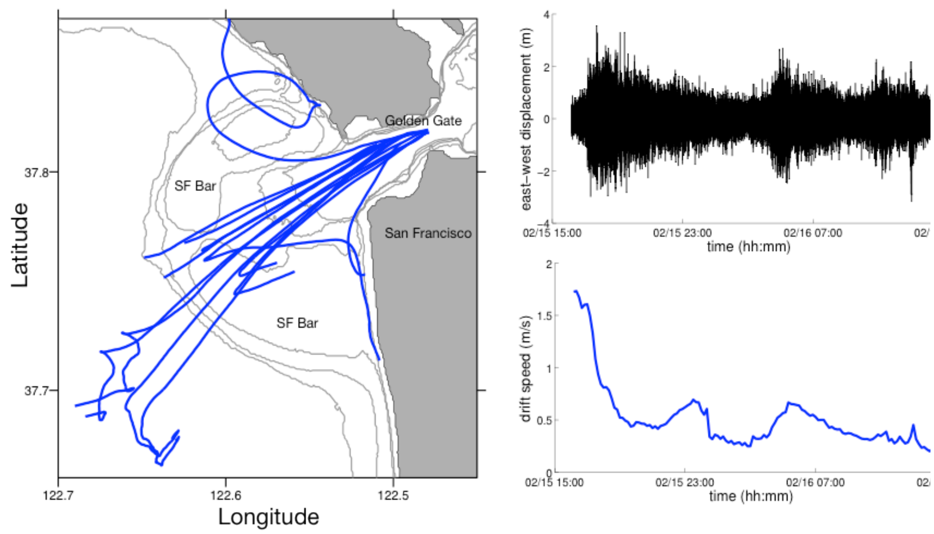

Figure 3 Results from the San Francisco Bight experiment. On 15 February 2012, Wave-Resolving Drifters (WRDs) were deployed at the Golden Gate bridge during ebb tide. Left panel show 14 tracks (blue curves) of drifters drifting toward the San Francisco Bar (the 4, 8, 12 and 16 m depth contours are drawn in grey contours); buoys were recovered 6 to 24 hours after deployment at the bar, further offshore, and on beaches north and south of the Golden Gate. Right panels show wave-resolved east-west motion (top) and 10-minute averaged drift speed (bottom) as recorded by the WRD following the most northerly track (see left panel).

To determine wave statistics from the highly non-stationary drifter time series we have experimented with cluster deployment of buoys such that statistics can be determined through ensemble averaging. Even in strong ebb currents, as present near the Golden Gate, the clustering of buoys showed very promising results and allows us to identify synoptic variations in wave statistics. An example result is shown in figure 4 for a 30-buoy deployment (6 clusters of 5 buoys). Wave heights were estimated in three spectral bands covering the lower-frequency swell, mid-frequeny wind sea, and the high-frequency spectral tail. Markedly different spatial evolution patterns are observed in these three bands. The swell evolution (upper right panel) shows strong focusing of wave energy on the ebb tidal shoal (region B), followed by a drop in energy behind the shoal (C), consistent with the expected depth-induced refraction. In contrast, the sea band (middle right panel) experiences little variation over the shoal but strong amplification further inshore (D) where the waves encounter the ebb tidal jet, suggesting the focusing is caused by refraction induced by current variations. The higher-frequency waves (lower right panel) are strongly suppressed near the entrance to San Francisco Bay (E), probably owing to blocking and dissipation in the opposing current. Work is underway to compare these observations with SWAN model predictions.

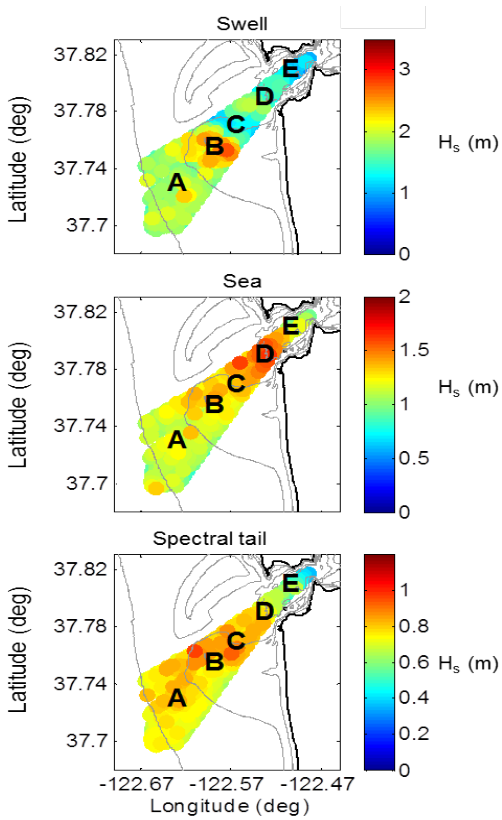

Figure 4 Spatial variability of surface wave energy in the San Francisco Bight. Six clusters of five Wave-Resolving Drifters (WRDs) were deployed in 10-minute intervals during the peak ebb current on 27 April 2012 near the Golden Gate Bridge. Significant wave height estimates within spectral bands were obtained on a dense spatial grid by emsemble averaging the observations for each cluster. From top to bottom wave height estimates are shown in the swell (0.07 – 0.15 Hz) band, wind-sea (0.15 – 0.25 Hz) band and high-frequency tail (0.25-1 Hz), respectively. (from Pearman et al, 2013, in review)

RESULTS

Model development

In areas of strong wave-current interaction, and in the presence of focusing, reflection, and blocking of waves, inhomogeneous and non-Gaussian effects are important. To improve modeling capability of such dynamics we have started development of a stochastic model that incorporates inhomogeneous effects in random waves, and can represent wave dynamics in focal zones (Smit & Janssen, 2013). The model is a natural extension of quasi-homogeneous theory (the radiative transfer equation used in third-generation wave prediction models) and can deal with inhomogeneities in wave fields of arbitrary spectral shape.

This quasi-coherent approximation resolves coherent interference contributions that are important in wave focal zones. The omission of such terms, such as implied in quasi-homogeneous theory, will result in dramatically different statistics in areas of strong inhomogeneity such as produced by interaction with current jets and coastal bathymetry (figure 5).

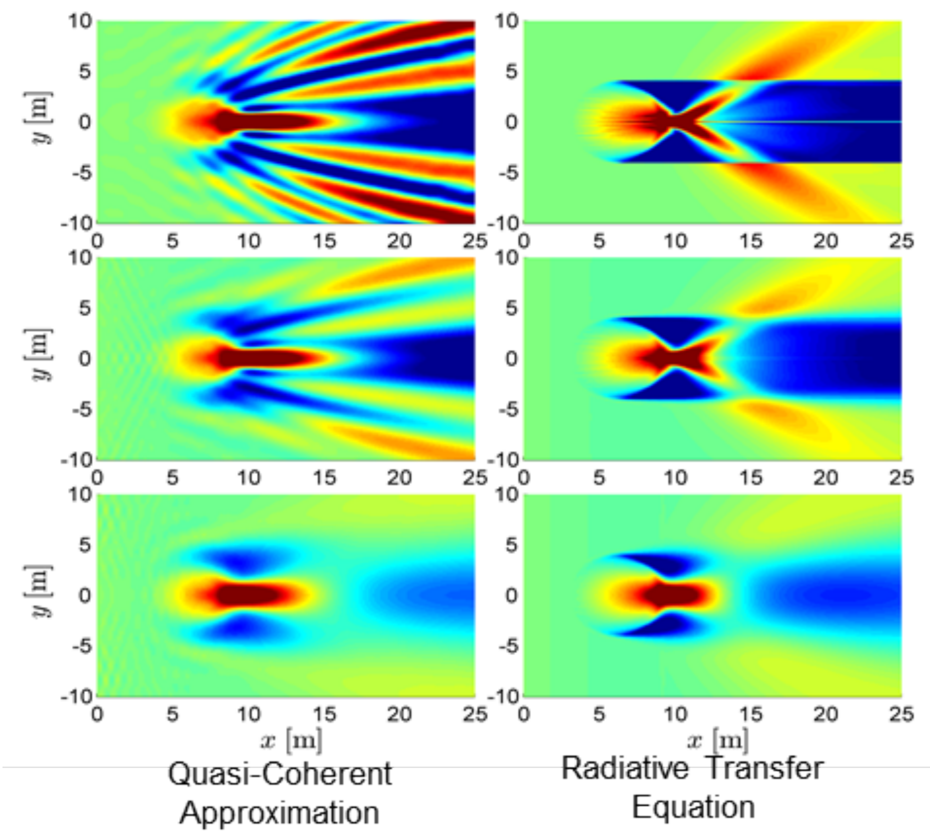

Figure 5 Quasi-Coherent (QC) stochastic model predictions of wave focusing over a shoal (left panels) are compared with predictions of the Radiative Transfer Equation (RTE) used in existing third-generation wave prediction models (right panels). Results are shown for three different incident wave fields: monochromatic waves (upper panels), narrow band swell (middle panels), and broad band wind waves (lower panels). The color shading indicates the relative wave heights ranging from a factor 2 reduction (dark blue) to a factor 2 amplification (dark red). Excellent agreement with the laboratory results of Vincent and Briggs (1989) confirms that the QC approximation accurately resolves the interference pattern of crossing waves behind the shoal (monochromatic and narrow band cases) that are absent in the RTE predictions. (from Smit and Janssen, 2013)

Mouth of the Columbia River (MCR) Experiment

The main focus of our research this past year was the experiment in the Mouth of the Columbia River (MCR), which took place in May/June 2013. Our primary objective was to observe wave-current interactions in the river mouth where large Pacific Ocean swells oppose unusually strong ebb tidal currents, coupled with significant river run-off in the spring season. The use of Lagrangian drifters is particularly well suited to this extreme environment, and therefore we concentrated our effort on deploying a massive number of drifters with a limited number of fixed instruments (a moored waverider buoy, three bottom pressure recorders, and a bottom-mounted ADCP) to provide some Eulerian observations.

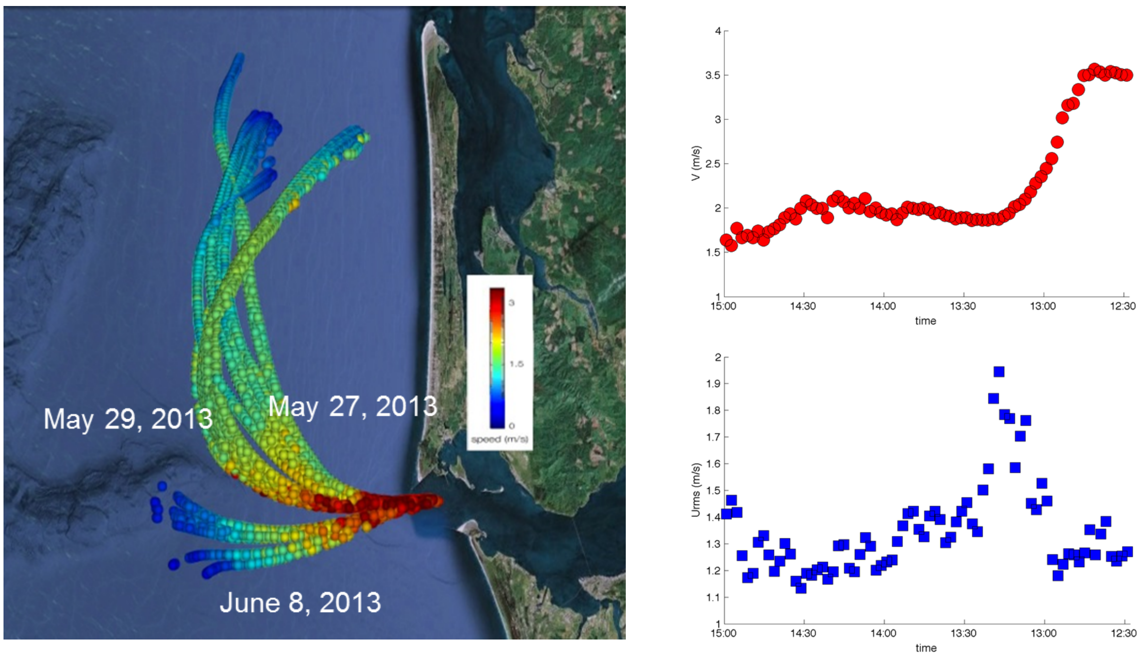

Figure 6 Drifter tracks from the three large ebb deployments. The right panels show a record of 2-min-mean currents and the associated rms fluctuation measured by one of the drifters on June 8.

In these extremely energetic conditions, maintaining the fixed array was a challenge (the waverider buoy failed after 4 days after getting run over by a vessel; the bottom-mounted sensors could only be deployed during the last week of the experiment owing to the extreme conditions during the first few weeks). In contrast, the drifter deployments were completed with relative ease and with remarkable success (only 2 drifters were lost in more than 110 drifter deployments).

We deployed drifters almost every day of the three-week-long experiment to study wave-current interaction and to support observations by other teams. The observations include three intensified drifter deployments at the peak of the ebb cycle on May 27 (27 drifters), May 29 (49 drifters), and June 8 (30 drifters). During these intensified ebb deployments, drifters were released at short (10-20 s) intervals near the time of maximum ebb current with the vessel maintaining its position.

During the May 27 and 29 deployments (see Figure 6), the drifters took a distinct northerly course after exiting the inlet and crossing the bar. During the June 8 deployment, the drifters split up in two groups, with a small cluster of drifters (the first in the water) taking a slightly more northerly route; all drifters continued approximately due west on this day after crossing the Columbia bar (in contrast to the more northerly tracks seen in the earlier deployments). The degree of dispersion also shows significant

differences with almost no dispersion on May 29 when all 49 drifters were recovered within a few km of each other about 27 km north of the river mouth.

To illustrate the observed spatial variability of currents and waves, a record of two-minute mean current speeds and root-mean-square (rms) current fluctuations is shown in figure 6 (as measured by one of the drifters deployed on June 8). The mean current, dominated by the tidal ebb flow, shows a rapid decrease from about 3.5 m/s in the channel to 2 m/s just offshore of the mouth. The rms fluctuations, dominated by the wave orbital motion, are strongly amplified over the bar reaching a maximum value of about 2 m/s. These unusually large fluctuations, associated with the strong wave amplification on the bar, on top of the tidal current, produce instantaneous velocities measured by the drifters that often exceed 5 m/s and thus momentarily change the direction of the flow!

To our knowledge these are the first detailed in situ wave and current observations in such an extreme environment, and we believe the data set will provide a unique opportunity to develop a better understanding of wave-current interactions.

To study the representation of the wave-focusing dynamics in operational wave models, we have conducted a hindcast study of the MCR observations with a preliminary SWAN model implementation (see Figure 7). The SWAN model was initialized with observations from the Astoria Canyon buoy operated by the Coastal Data Information Program (CDIP, buoy # 46248). Three-dimensional current fields and bathymetry were provided by the Center for Coastal Margin Observations & Prediction (CMOP).

The SWAN model shows an area of wave focusing due to bottom and current refraction near the river mouth (see Figure 7). Although qualitatively consistent with the observed focusing, the observations indicate that wave heights in the focal zone are much larger than predicted and that the wave height variability is much more abrupt. In other words, the model predicts focusing in a larger area, but underestimates the strongest amplification effects considerably. Although these results are preliminary, they indicate that there are still large improvements to be made in the representation of wave focusing in coastal inlets by operational wave models. By providing a spatial snapshot of the wave evolution, the drifter data used in this way, provides a new and unique opportunity to test and improve wave models.

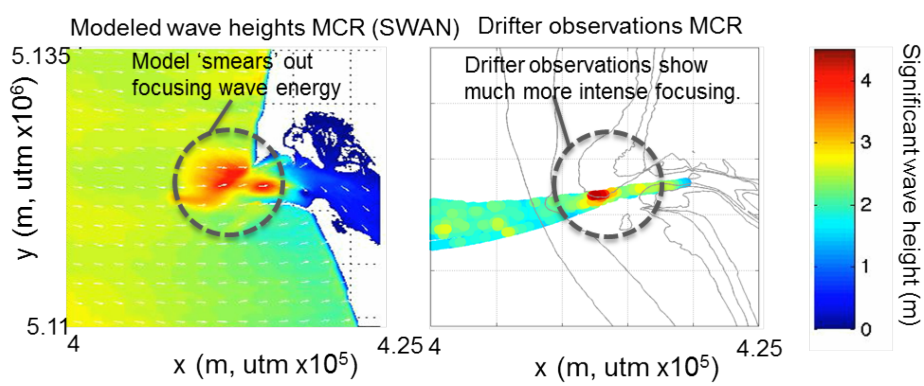

Figure 7 Preliminary model results for the June 8 ebb deployment. Left panel: SWAN predictions of significant wave height (color) and mean wave direction (arrows). The model was initialized with wave measurements from CDIP buoy 46248 located at the tip of the Astoria Canyon, and uses modeled current fields provided by CMOP. Right panel: wave height statistics observed with drifters using the same ensemble averaging approach applied to the Golden Gate data set. The dashed circle highlights the strong amplification of waves on the ebb tidal shoal. (from Pearman et al., manuscript in preparation)

IMPACT/IMPLICATIONS

The development of inexpensive drifter buoys equipped with GPS sensors and accelerometer packages that resolve both surface waves and surface currents, has extended observational capability to areas where it is difficult to deploy and maintain moorings (such as in strong currents and/or energetic waves).

The observations of wave-current interaction in the presence of variable (tidal) currents, topography, and stratification, will contribute a comprehensive new data set that will improve our understanding of wave variability in coastal inlets and river mouths. These observations can be used to test theories and models, either existing, or those developed within the scope of this study.

The development of a stochastic wave model that resolves inhomogeneous effects in random waves, is an important and critical step to develop statistical modeling capability of wave dynamics in complex coastal environments.

RELATED PROJECTS

The development of the GPS-tracked drifter buoys was started as part of the ONR HiRes DRI to enable deployment of a greater numbers of instruments to capture the spatial variability of waves and currents. The instrument development and deployment strategies planned in the present project build on our findings during the HiRes DRI. The development of a transport model for non-Gaussian and inhomogeneous wave fields also contributes to, and benefits from, progress in the ongoing Wave Modeling NOPP. The data collected in this project will also be of use in validation on new model parameterizations developed in the NOPP project.

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